Coronagraph Technology Assessment

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May 28, 2008

Coronagraph Technology

- Internal Coronagraph Requirements
- Coronagraph Masks
- Mirror Technology
- Deformable Mirrors
  - John Trauger's Team Developments
  - Material Science Considerations
  - Cost
- Thermal
- Isolation Systems
- Coatings, Dichroics and Beam Splitters
- Detectors

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Technology Criticality & Milestones

Internal Coronagraph	WFSC			Masks & Stops	Telescope / Mirror Technology	Modeling: Tools & Validation		Pointing	Thermal Control	Detectors	System Verification & Validation
	Raw Instrument Contrast	DMs	Algorithms			Optical	Integrated: optical/Thermal/Mechanical				
Space 0.5m	1.00E-07							2 mas	~ mK		
Space 1.5m	1e-10 @ 10-20% bandwidth							0.5 mas	~ 0.1 mK		
Space 4m	1e-10 @ 10-20% bandwidth							0.5 mas	~ 0.1 mK		
Space 8m	1e-10 @ 10-20% bandwidth							0.5 mas	~ 0.5 mK		

External Coronagraph	Raw Instrument Constrast	Deployment		Coronagraph	Telescope / Mirror Technology	Modeling: Tools & Validation		Pointing & Alignment	Occulter Thermal Control	Detectors	System Verification & Validation
		Mechanisms/Inflatables	Edge effects			Optical & Scaling	Integrated: optical/Thermal/Mechanical				
4m Telescope w/ 50m Occulter	1e-10 @ 100% bandwidth			N/A							
4m Hybrid w/ 36m Occulter	1e-10 @ 100% bandwidth										

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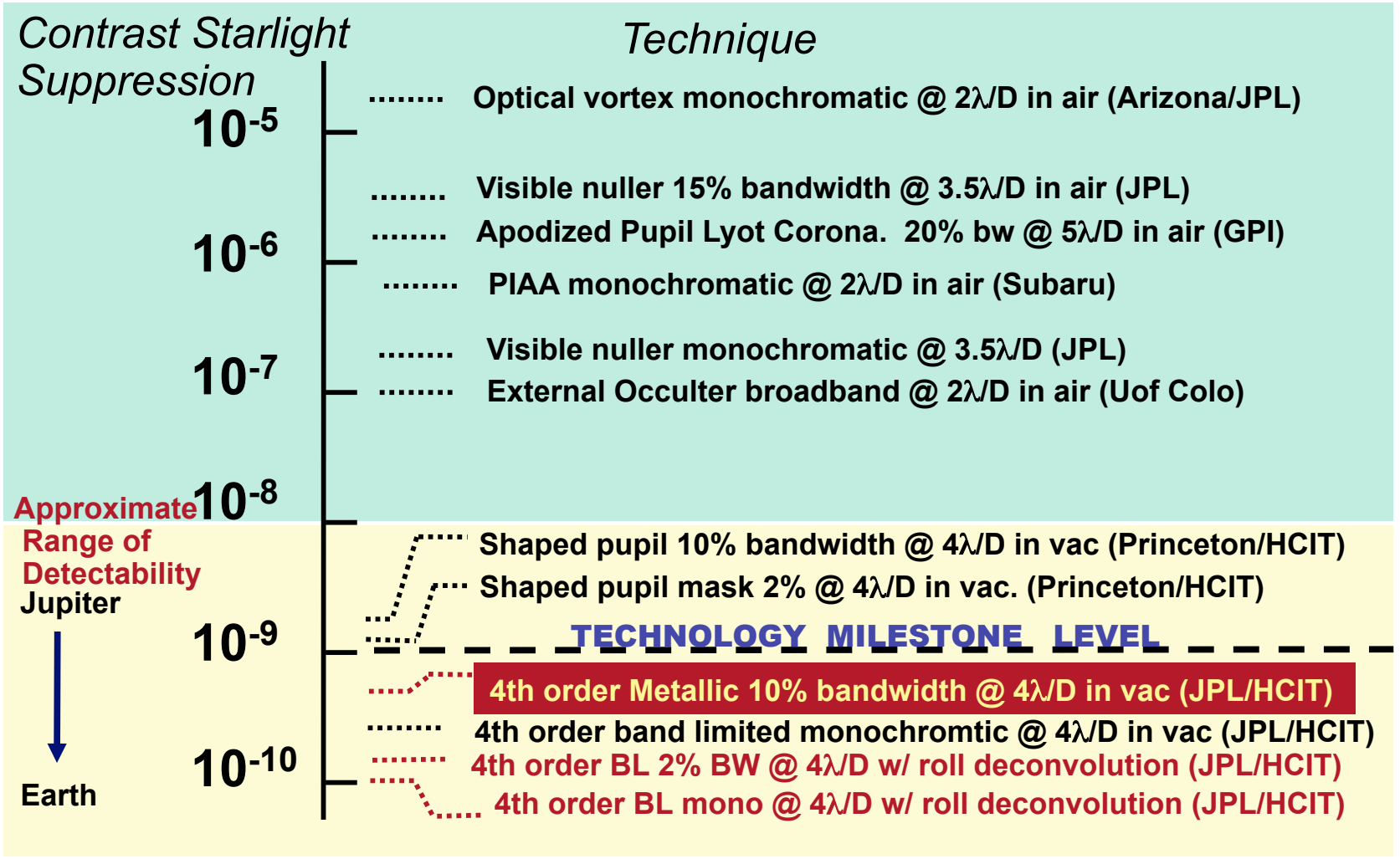
ASMSC Exoplanet Infrastructure Support

ExoPlanet Exploration Program

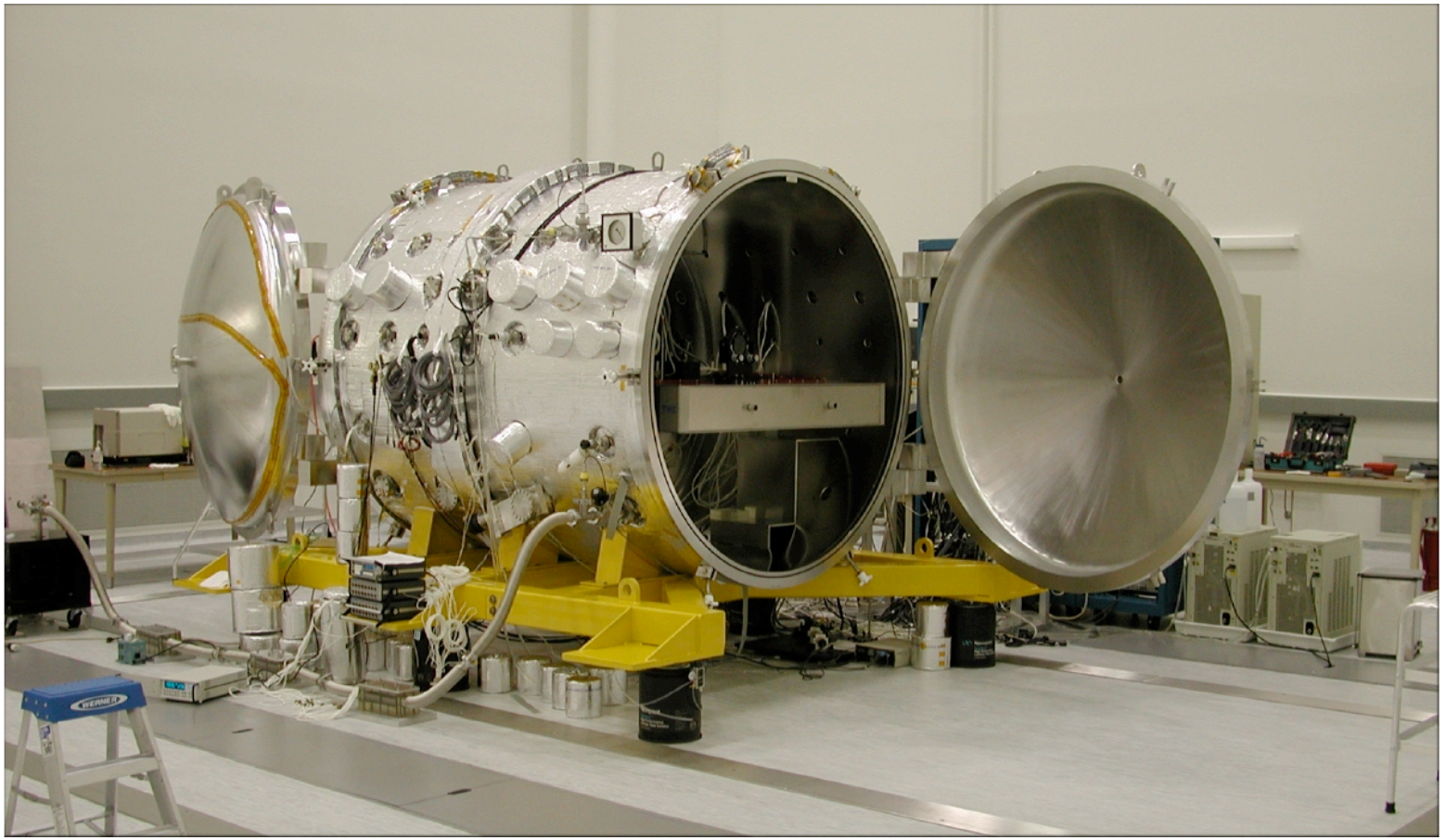
Astrophysics Strategic Mission Concept Studies - Exoplanet Science *6 Coronagraphs out of 19 Selected Concepts = 32%*					
Name	**Instrument**	**Size**	**PI Affiliation**	**Category**	**Infrastructure Support Requested**
PECO Pupil-mapping Exoplanet Coronagraph Observer	PIAA	1.4m Telescope Medium Class	Olivier Guyon Univ of Arizona	Internal Coronagraph	• HCIT Demo • Detector Expertise • WFSC infrastructure (nulling algorithm, DMs) • Modeling infrastructure (testbed verification, spectral characterization, orbit determination, integrated modeling) • Fabrication of PIAA occulting masks
ACCESS	Band-Limited Dielectric, PIAA, Shaped-Pupil, Vortex, 4QPM	1.5m Telescope Medium Class	John Trauger JPL		• HCIT Demo for each coronagraph technology: Band-limited, Shaped-Pupil, PIAA, Vector Vortex • WFSC infrastructure (2-DM nulling algorithm, additional DMs) • Fabrication of metallic & dielectric masks
XPC eXosolar Planet Characterization	Hybrid: Internal / External	4m Flagship w/ 30m Shade	David Spergel Princeton		• Fabrication of External Occulting masks • Modeling infrastructure (integrated modeling, diffraction modeling for occulter tolerancing, GNC, navigation & completeness optimization)
NWO New Worlds Observer	External Occulter	4m Flagship w/ 25m/50m Shade	Webster Cash - Univ of Colorado	External Coronagraph	No support requested
DAVInCI	Dilute Aperture Visible Nuller	4x1.2m Flagship	Mike Shao JPL	Internal Coronagraph / Interferometer	• Vacuum testing of components • DM calibration • PSF calib w/ 4 beam nuller • Modeling Infrastructure Support
EPIC	Visible Nuller	Medium Class	Mark Clampin - GSFC		
Planet Hunter	Astrometric Interferometer	Medium Class	Geoff Marcy UC Berkeley	Interferometer	None required

Coronagraph Technology Status April 2008
Starlight Suppression Laboratory Results

ExoPlanet Exploration Program

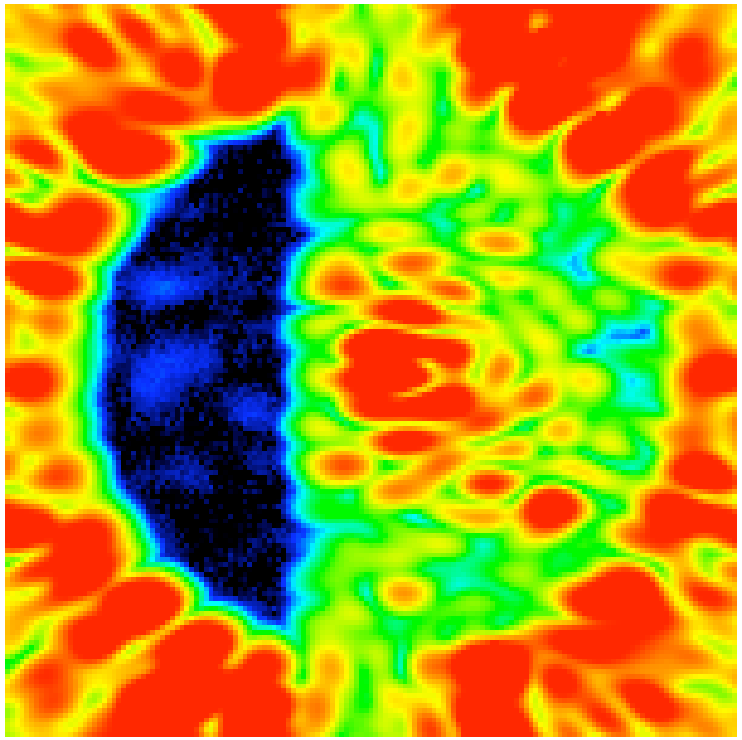


High Contrast Imaging Testbed at JPL



HCIT JPL testbed results

Contrast in 760-840 nm (10%) bandwidth



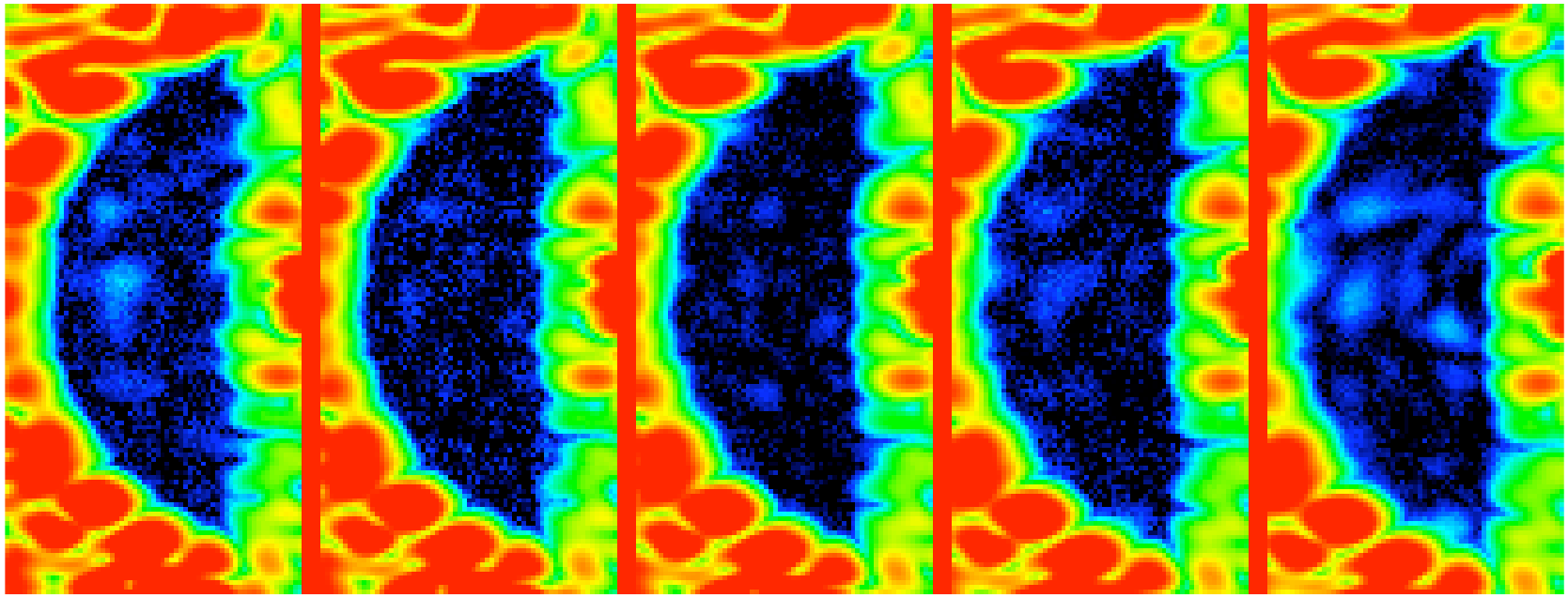
Contrast averaged across five multi-wavelength EFC iterations over a 5 hour period:

Inner 4-5 lambda/D box:
C = 5.2 e-10

Outer 4-10 lambda/D box:
C = 7.5e-10

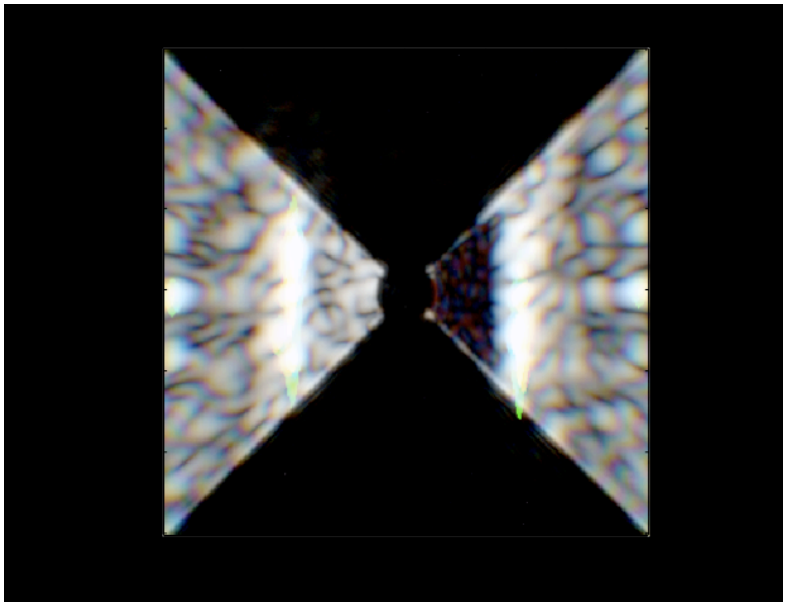
Moody, Gordon, Trauger - May 2008

Contrast across five contiguous 2% passbands

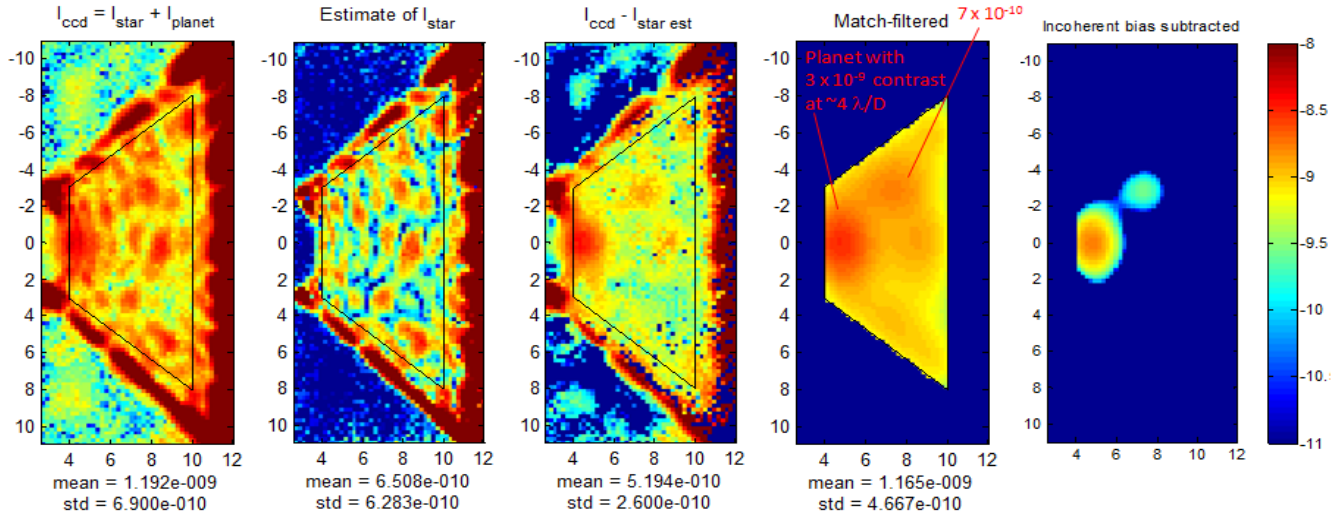


	768 nm	784 nm	800 nm	816 nm	832 nm
C(4-5)	9.8e-10	6.7e-10	6.5e-10	3.9e-10	3.2e-10
C(4-10)	11.5e-10	6.3e-10	5.2e-10	6.2e-10	11.4e-10

Shaped Pupils



Best suppression achieved with Shaped Pupils:
2.4e-9 contrast at 4 lambda/D from 760-840nm.



Mask Fabrication technologies

- Amplitude masks (continuous, half tone techniques)
  - *phase & chromaticity of the phase*
- Phase masks
  - *Focal plane (4QC, OVC)*
- Etching (DRIE)
  - *Shaped pupils, Lyot Stops*
- Aspheric polishing / etching
  - *PIAA, Phase plate coronagraph*

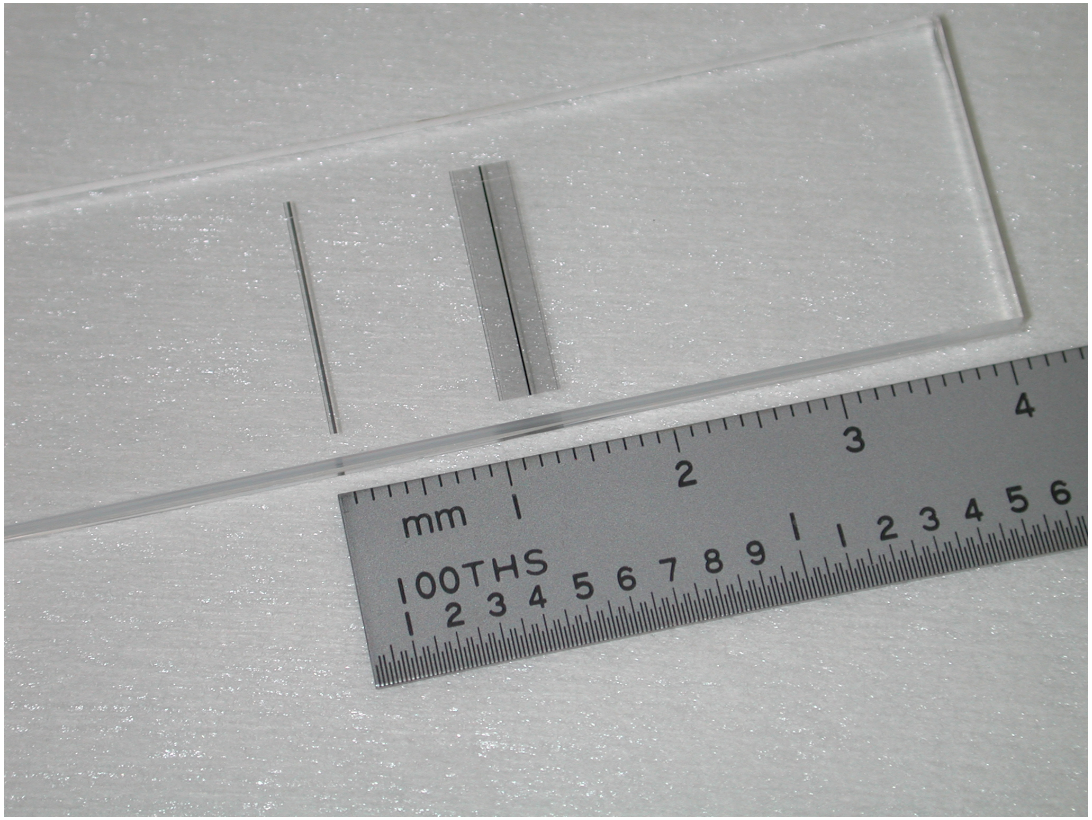
Mask Fabrication technologies

Predicted coronagraph contrast with metal and metal-dielectric masks

Example	Configuration	Bandwidth ($\delta\lambda / \lambda$)	C (4-5 λ/D) $\times 10^{-10}$	C (4-10 λ/D) $\times 10^{-10}$	ε	Lyot throughput
1	HEBS IK89	10%	4.1	1.5	0.47	42.4%
2	Nickel	10%	3.7	1.4	0.36	55.1%
3	Ni + MgF_2	10%	0.38	0.76	0.26	67.2%
4	Ni + MgF_2	20%	3.7	3.8	0.26	67.2%
5	Ni + MgF_2	30%	5.1	6.0	0.27	66.0%

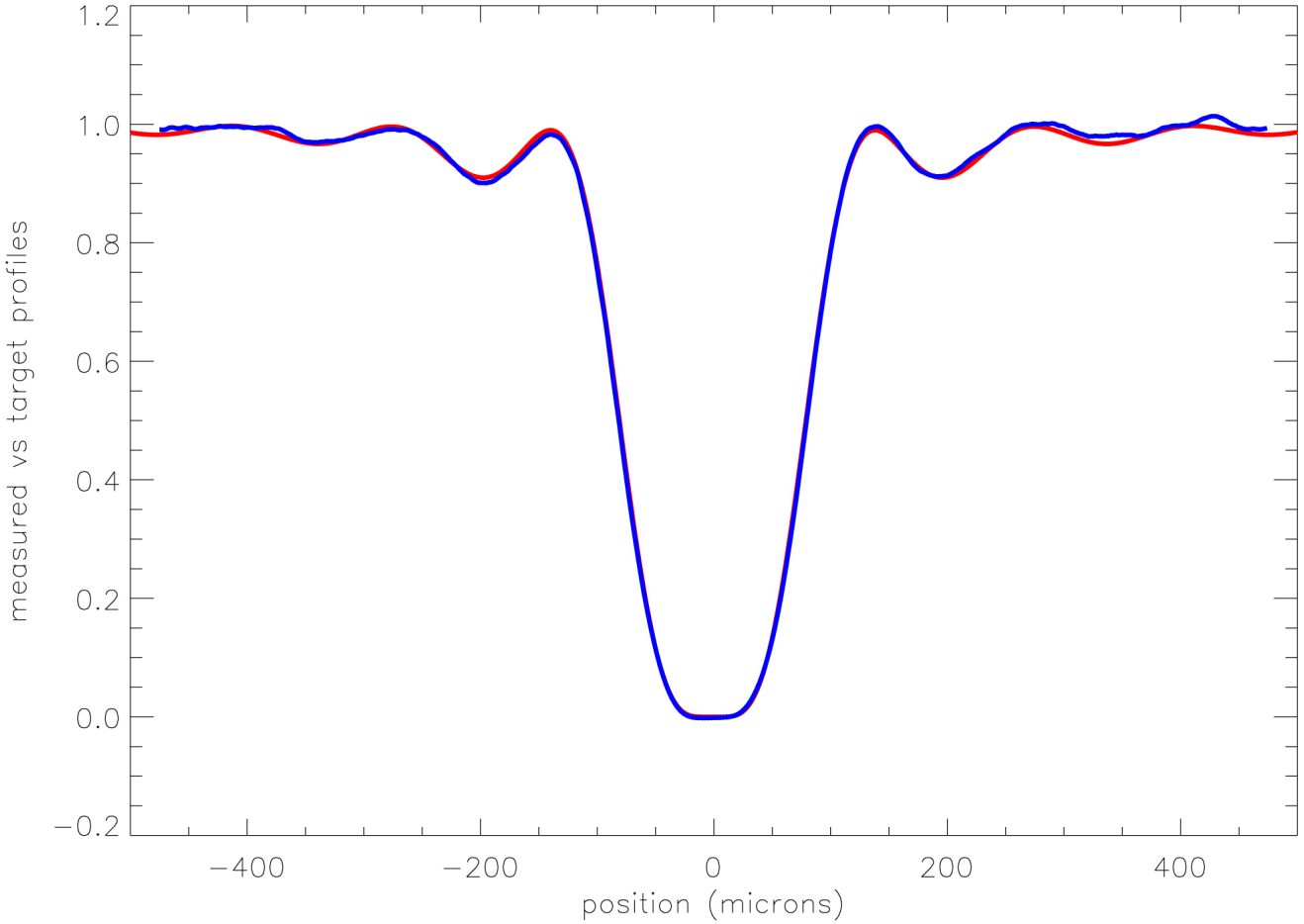
Predicted contrast, bandwidth, and throughput for the nickel occulter, with comparisons to metal/dielectric and HEBS, from Moody & Trauger (2007).

Metallic mask for April 2008 experiments



Nickel occulter (fabricated 1/15/08) vacuum-deposited on a fused silica substrate. Occulter is the linear pattern at right, at left is a calibration pattern.

Metallic mask for April 2008 experiments

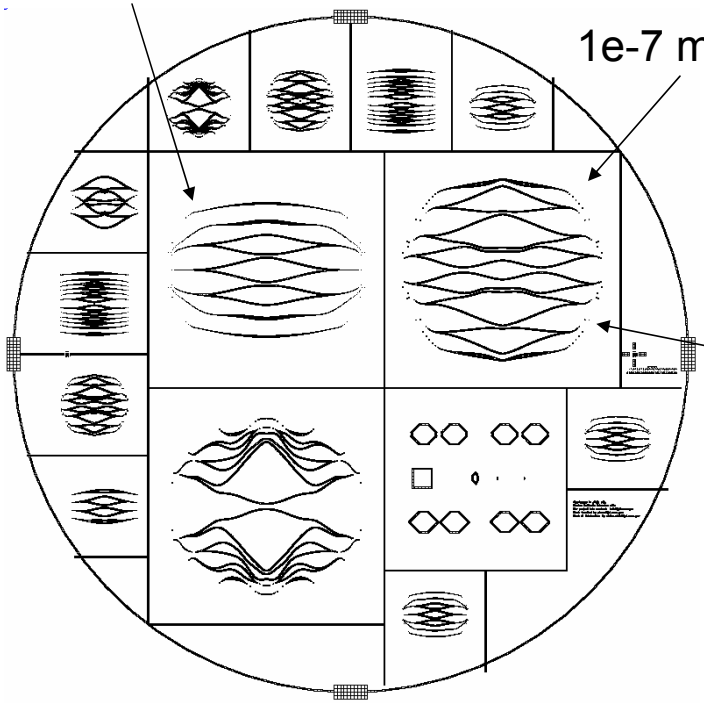


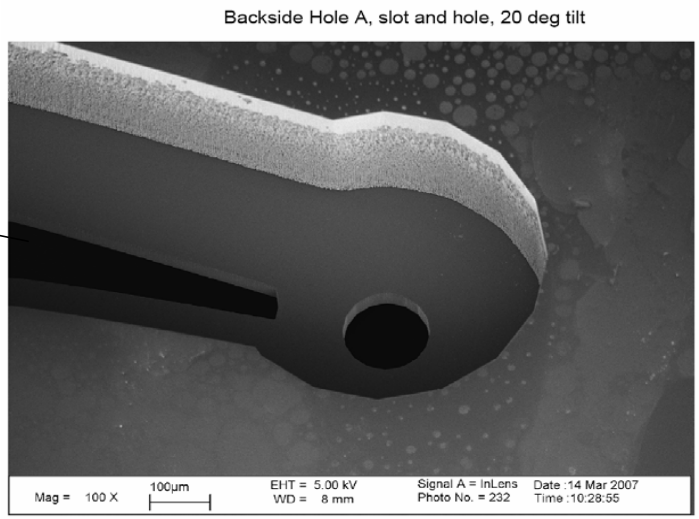
Comparison of the intensity transmittance profiles as specified (red) and as measured (blue) in the 080115 deposition run.

Etching

1e-9 mask

1e-7 mask with 3 lambda/D IWA





Smallest features are ~ 5 microns.

Silicon-on-Insulator wafers.
DRIE process. 2-sided etching.
Manufactured at JPL Microdevices Laboratory

A process is designed for making a 1e-10 free-standing mask, but not demonstrated yet.

Mission size	Small	Large
Lyot Coronographs	Models generated using conventional Fourier. calculations have been validated versus HCIT for bandlimited occulters to contrasts of ~5e-10 in broadband light.	Models expected to work accurately down to 1e-10 contrast and better, but have not been fully validated. Polarization is a concern. Simulations for a TPF-like system with wavefront control have been run.
Shaped Pupils	Models validated versus HCIT. Conventional Fourier methods can be used with some additional input from analytical calculations to accurately handle the narrow parts of the masks.	Vector propagation analysis comes into play at <1e-10 contrasts. Ability to work with wavefront control in broadband light at these levels has not yet been shown. Tiny mask defects are important at these contrasts.
Phase Masks	Models have not been validated below 1e-6-1e-7 contrast. Most techniques cannot be accurately implemented with conventional Fourier techniques with some additional analytical input due to sharp phase discontinuities. Scattering effects from sharp edges are not easy to model.	Little work has been done to verify models to 1e-10 contrast level, and no work with integrating the models with wavefront control to investigate broadband performance with aberrations present.

Mission Size	Small	Large
PIAA	Cannot accurately model using straightforward techniques, especially with wavefront errors present. Need to integrate ray tracing and propagation. Models have not been validated to anywhere near 1e-9 contrast.	Accurate modeling at 1e-10 levels with aberrations and wavefront control appears daunting, and no complete and efficient method of propagation has been proposed (approximations have been suggested, but they require additional apodization of the system to avoid calculating some diffraction effects, and thus are incomplete models).
Occultor		Models have not been validated to anywhere close to 1e-10 contrasts. Modeling small errors on the occulter requires non-Fourier methods that compute piecemeal propagation. Hybrid concepts have not modeled systems with occulter+wavefront errors with control.
Visible Nuller	Models have not been verified below ~1e-6 contrast. Effects of fibers, if used, cannot be accurately modeled with conventional Fourier techniques.	No model validation, integration of wavefront control at these levels has not been demonstrated.

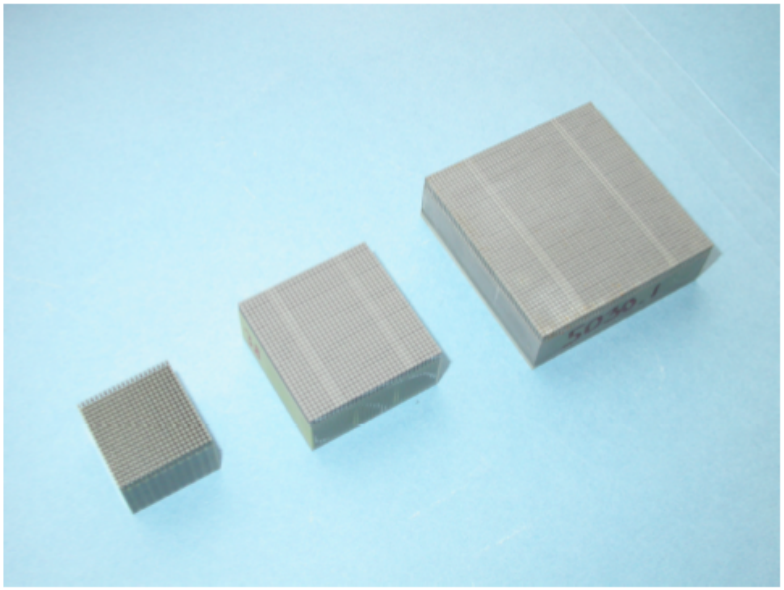
Deformable Mirror Technology

Deformable Mirror Technology demonstrated on the HCIT

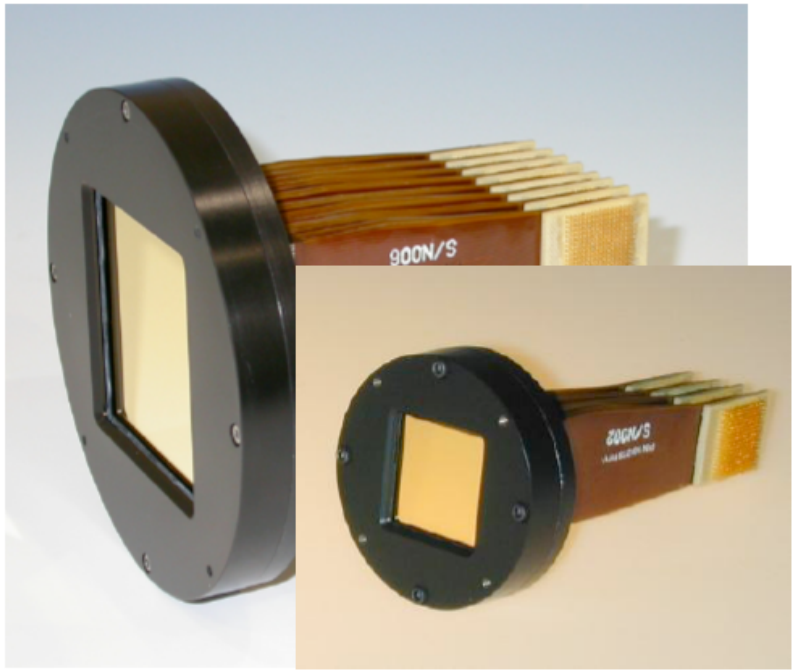
John Trauger, Amir Give'on, Brian Gordon,
Brian Kern, John Krist, Andreas Kuhnert
Dwight Moody, Peggy Park, Wes Traub, Dan Wilson

Jet Propulsion Laboratory, Caltech

Deformable mirror development for HCIT

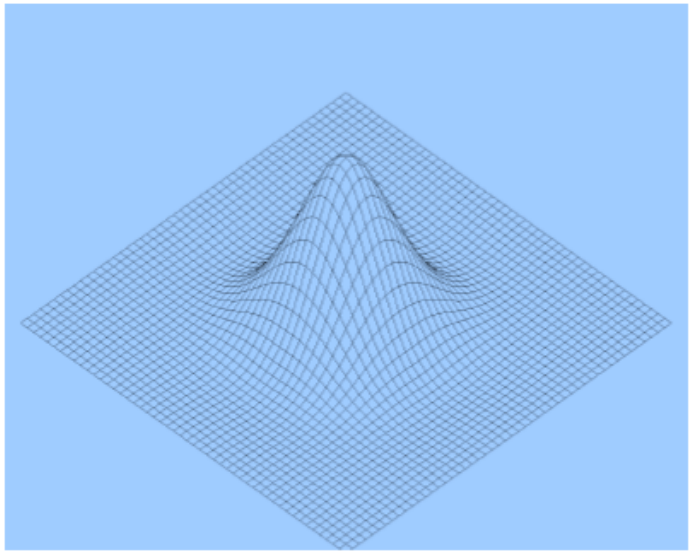


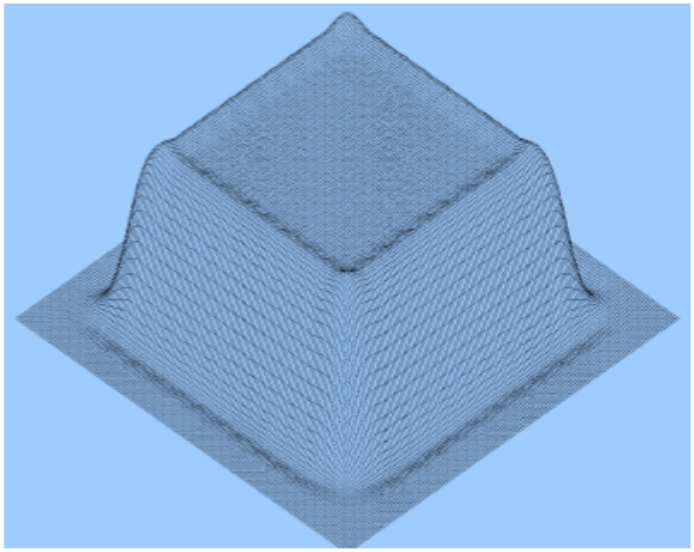
Evolution of monolithic PMN actuator arrays by Xinetics: 21x21, 32x32, and 48x48 arrays. A fused silica facesheet is bonded to the actuator array (top side). Electrical connections (on the bottom side) complete the DM.



DMs delivered to JPL by Xinetics. Larger arrays are formed by bonding modules together: here a 64x64 array is built up with four 32x32 modules. Mirror surface is polished to λ/100 rms. Surface figure (open loop) is stable to 0.01 nm rms.

DM surface influence function





At left: The empirical surface deformation profile of a single actuator. Grid spacing is 0.1 mm, actuators are positioned in a square array with 1 mm pitch.

At right: Mirror surface predicted by the summation of individual actuator influence profiles in an 11x11 actuator block pattern.

Wavefront Correction Technologies

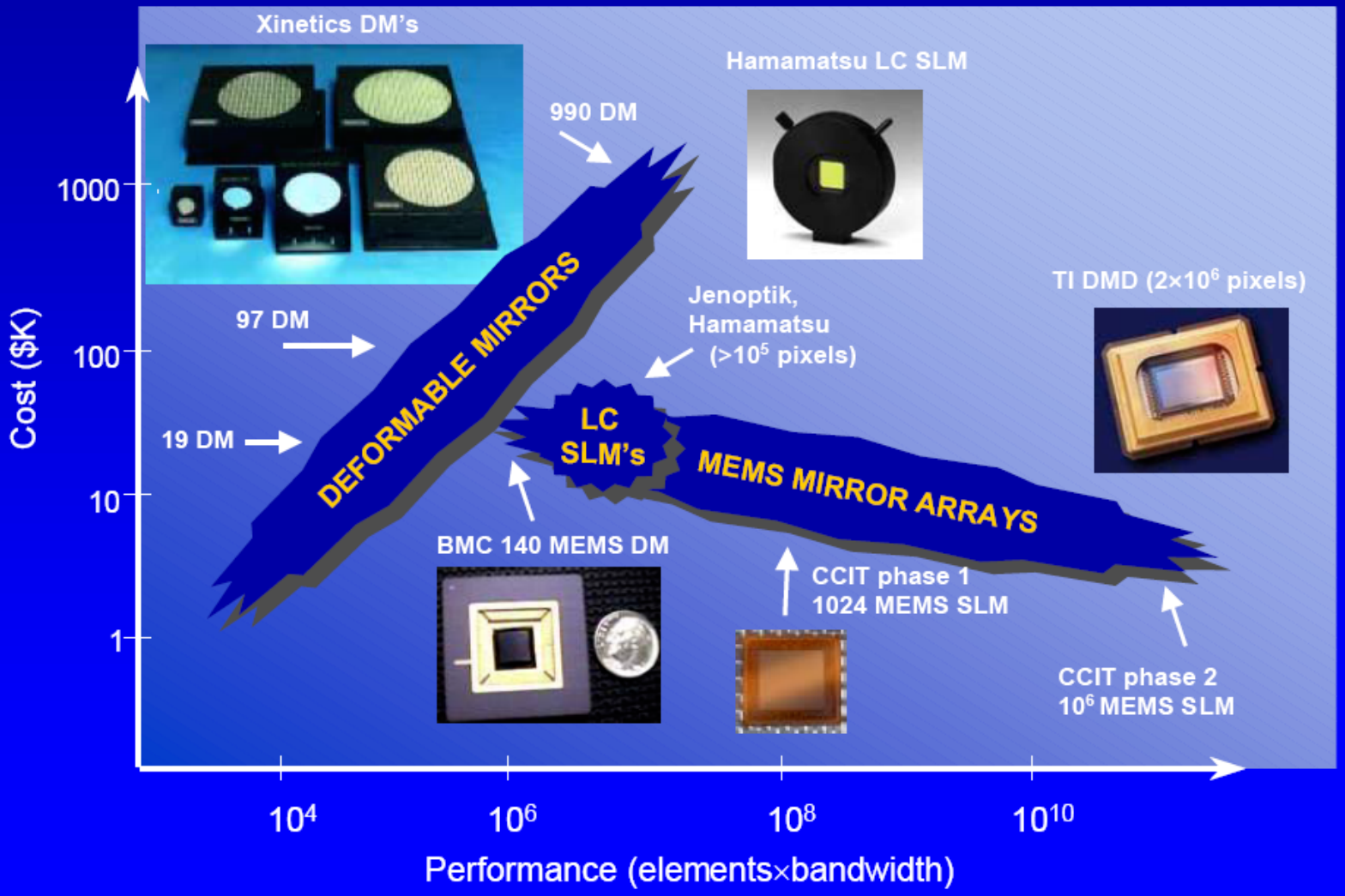
Scot S. Olivier

Adaptive Optics Group Leader
Physics and Advanced Technologies
Lawrence Livermore National Laboratory

Associate Director
NSF Center for Adaptive Optics

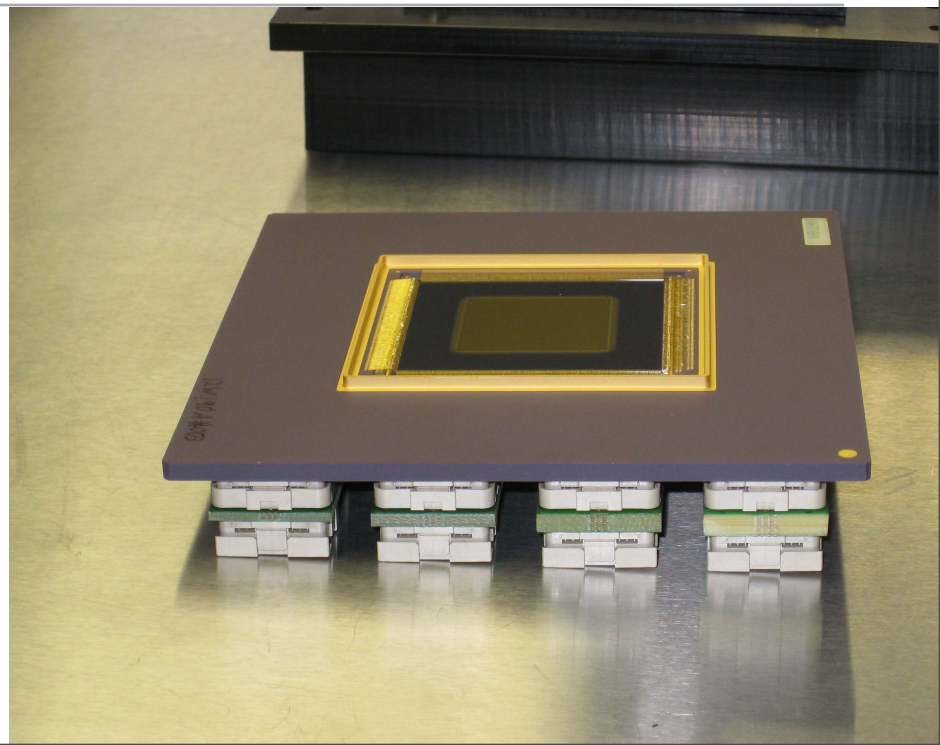
August 7, 2003

New wavefront control devices provide dramatically increased capabilities at lower cost



MEMS Deformable mirrors

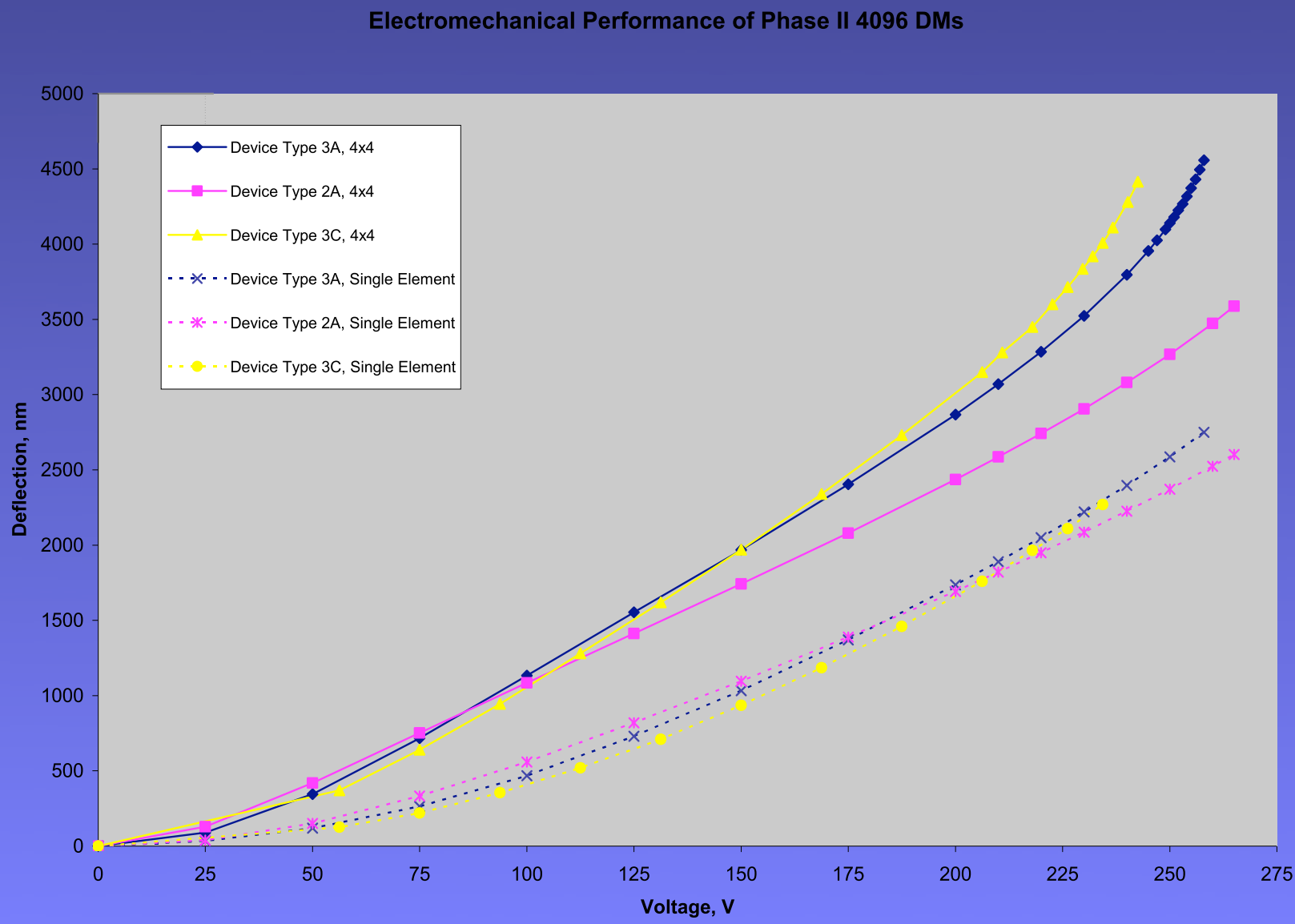
Inputs from Boston Micromachines
Dave Palmer (LLNL), GPII



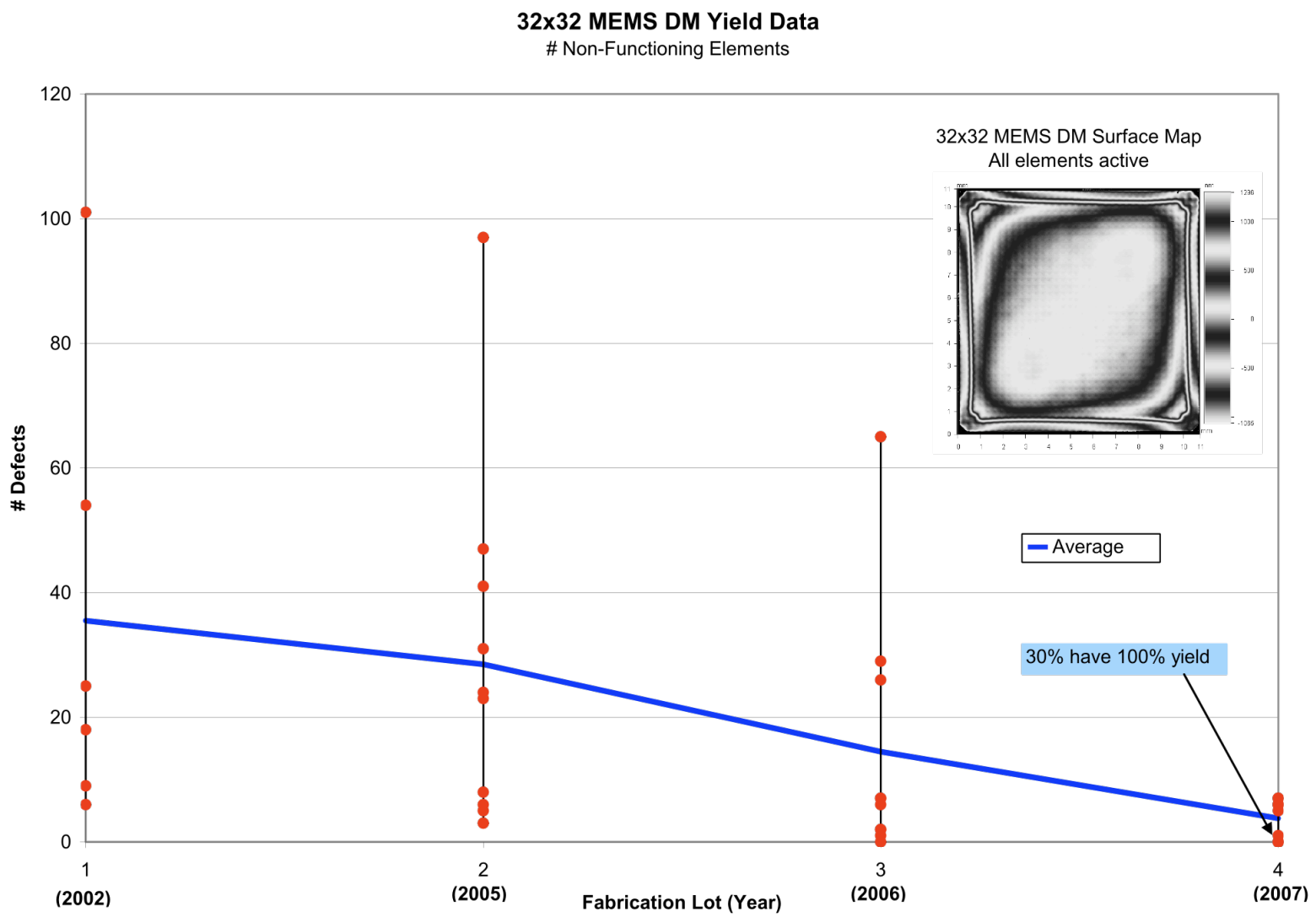
Key MEMS Requirements

Description	Requirement
Pixel count	4096 (64x64)
Pitch	400 microns
Stroke	3 um, surface, after mirror is flattened
Pixel surface finish (P-V)	< 30 nm (goal: <9 nm)
Flatness over aperture (sphere removed) (RMS)	goal: <70 nm
Neighboring actuator differential stroke	> 1 um, P-V, for a sin wave with a period of 2 actuators
Good actuators	all actuators on a 48 actuator diameter circle must work to full specification
Uniformity of surface reflectivity	+/-1% RMS at all spatial frequencies, measured with a spatial resolution of 1 actuator
Operating temperature, with device still meeting other specs	-5 to 20 degrees Celsius

Stroke vs. Voltage For Three Prototype Actuator Designs



Evolution Of Device Yield (Non-Functional Actuators) As A Function Of Fab Run



Veeco Interferometer Data Of A Single Actuator

Veeco

Mag: 3.9 X
Mode: PSI

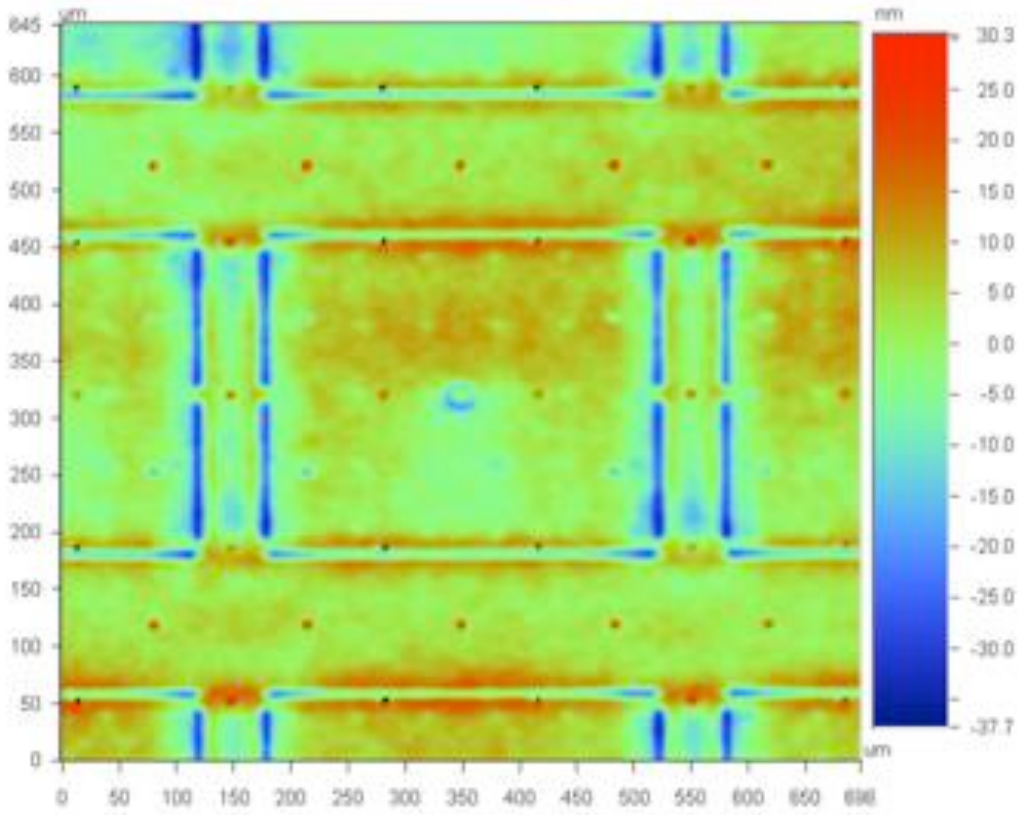
Surface Data

Date: 03/26/200
Time: 09:24:14

Surface Statistics:
Ra: 5.14 nm
Rq: 7.21 nm
Rz: 61.69 nm
Rt: 68.08 nm

Set-up Parameters:
Size: 279 X 258
Sampling: 2.51 um

Processed Options:
Terms Removed:
None
Filtering:
None



Title: 12w190A#001
Note: Device Design Type 3a

Materials Science Considerations in the Development of the Coronagraph Deformable Mirror

Robert E. Rudd, Physicist

Lawrence Livermore National Laboratory
7000 East Ave., L-045
Livermore, CA 94550 USA

May 19, 2008

Yield Phenomena

- Silicon is a brittle material and exhibits little plastic flow; however, microscopic plasticity may still be relevant.
- The local shear stress within the membrane changes as the membrane is subjected to:
  - stress due to thermal expansion,
  - forces acting on the support structure, or
  - changes of voltage on the actuators.
- If the local shear stress is sufficiently high, dislocations within the membrane move, causing plastic deformation.
  - This phenomenon is potentially relevant to the question of membrane stability because it is a thermodynamically irreversible process and causes hysteresis.
  - Dislocations terminating on the surface are associated with surface steps, sub-nm scale features. Even before intersecting a surface, the elastic stress fields emanating from a dislocation can cause the displacement of a surface.
- Since polysilicon is strong, it may be that plasticity is not important for the relatively small DM deformations needed in the coronagraph application, but an assessment of the effect of plasticity should be made.

Other Material Effects

- Creep
  - Creep is an irreversible process of plastic flow due to the slow relaxation of stress as a result of stress-driven point defect diffusion.
  - Creep is typically only significant at elevated temperatures or extremely long time scales.
- Elastic Anisotropy
  - Silicon is a cubic crystal in the diamond cubic crystal structure.
  - Single crystal silicon is moderately anisotropic.
  - Polycrystals with a random texture (random grain orientation) is elastically isotropic on length scales that are large compared to the grain size.
  - Given stresses generated during DM operation and a knowledge of the grain structure, it is straightforward to calculate changes in the surface morphology due to elastic anisotropy.
- Anisotropic Thermal Expansion
  - Surface roughening can occur due to anisotropic expansion of the crystal grains even under a uniform heating.
  - This is not an issue for silicon, gold or aluminum, since thermal expansion of cubic

Annealing

- The polysilicon membrane may be annealed prior to the deposition of the metal coating.
  - Such annealing would provide the thermal energy for dislocations to flow, leading to a reduction in the residual stress and the associated dislocation network.
  - Relaxing the residual stress may have the desired effect of reducing local stress and the associated surface deformations at the expense of spreading it across a smooth curvature of the DM, which is more easily countered with the actuators.
- Annealing typically reduces the yield stress of the material, although in the brittle Si this change may not be significant.

BACKUP slides

Coronagraph requirements

Mission type/size	Raw Contrast	Augmented contrast	IWA λ/D	Pointing	Mid Spatial WF stability*	Thermal stability	Optics Quality & Fabricatn	Driving science
Internal Coronagraphs								
Ground based 8-m ExAO	1.00E-06	1.00E-07	5	10 mas	5 nm	N/A	x	Young giant planets, debris disks
Ground based 30-m ExAO	1.00E-06	1.00E-08	3	5 mas	5 nm	N/A	x	Formation of planetary systems
Space 0.5-m	1.00E-07	1.00E-07	1	2 mas	1 nm	~ mK	x	debris disks

Mission type/size	Raw Contrast	Augmented contrast	IWA λ/D	Pointing	Mid Spatial WF stability*	Thermal stability	Optics Quality & Fabricatn	Driving science
Internal Coronagraphs								
Space 1.5-m	1.00E-10 @ 10-20% bandwidth	1.00E-10	~2	0.5 mas	30 pm	~ 0.1 mK	x	Super Earth to Jupiters, R = 15
Space 4-m	1.00E-10 @ 10-20% bandwidth	1.00E-11	2-3	0.5 mas	30 pm	~ 0.1 mK	x	Earths to Jupiters, R = 40
Space 8-m	1.00E-10 10-20% bandwidth	1.00E-11	3-4	0.5 mas	30 pm	~ 0.5 mK	x	R=100 Spectroscopy on Earths